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Design and Performance Evaluation of Hybrid Photovoltaic Thermal Solar Dehydrator

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ABSTRACT

This paper reported on the design and performance evaluation of a hybrid photovoltaic thermal solar dehydrator. The dehydrator is designed to suit the needs of household users and small industries and works using a hot air mechanism. The design process commenced with the initial sketches to collect related ideas and design concepts. The design was then proceeded to concept evaluation through a decision matrix to select the best option. The final design was then converted via computer-aided design (CAD), SolidWorks 2021 to a 3D model and fabricated into a full-scale prototype. The drying performance of the dehydrator on food was evaluated and compared with traditional drying under the meteorological conditions of Panchor, Muar, Malaysia. Heat accumulated inside the dehydrator resulted in a temperature of 44.1 degrees Celsius which is 20 % higher than the ambient temperature. The performance analysis demonstrated that the drying speed of a hybrid solar dehydrator is moderately slower than traditional drying, but it provided a more hygienic drying environment and preserved the color and nutrition value of food products.

Keywords:
Dehydrator; hybrid photovoltaic thermal solar; food drying

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1. Introduction

Food drying is a method of food preservation. It can be traced back to 8000 BC when the first known drying installation was introduced in the South of France [1]. It preserves food by reducing the water content and water activity in the product by evaporation using heat [2]. Removing the moisture content present in the product results in bringing down the rate of growth of microorganisms that leads to decay and deterioration of the product. This further helps in reducing the weight of the product and cutting down the storage space, also, increasing the shelf life of the product where it can be stored for a longer time.

There are a variety of dehydrating methods available nowadays. These include the traditional sun-drying method, which is usually employed by households and small-scale industries. The

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methods have inherent limitations, including high crop losses due to inadequate drying, fungal attacks, insects, birds, and unexpected weather changes [3]. Convective drying can also be used for food drying. As it provides short drying times, it is frequently used in the medium-sized to the large-scale industrial sector. In this method, the dehydrator works by forcing the hot air that was heated by an electrical induction heater or gas burner to pass through the food. This evaporates the moisture content in the dried food. However, the dehydrator for convective drying is typically larger in size and requires a high initial and operation cost. In addition, its dependence on electricity and gas makes it unpopular for small-scale industries.

Solar dehydrators seem to be one of the most ideal solutions for small-scale industries in Malaysia that are trying to reduce food costs [4-5]. It is because Malaysia's climate is characterized by consistent temperatures, high humidity, moderate winds, and abundant rainfall [6]. Being a country located in the equatorial region, this favorable geographical location enables Malaysia to receive an abundant amount of solar radiation throughout the year. It is estimated that Central Peninsular Malaysia receives an average of 6 hours of sunlight per day [7].

A solar dehydrator can be classified into two major groups which are active and passive [8]. Lakhani *et al.,* [5] introduced their design of a solar dehydrator for fruit chips. The solar dehydrator was fabricated by making use of locally available and relatively cheap materials. However, the entire casing of the dehydrator is constructed with wood which is unsuitable for tropical zone since the dehydrator will be applied outdoor for a long time. In addition, wood is not resistant to dampness and can rot where it is liable to mold under high humidity conditions. Besides that, to satisfy the requirements of rural areas, Emetere *et al*., [9] designed a solar dehydrator that was cheaper and inexhaustible. During the drying process, the heated gases would flow up and escape from the chimney at the top. However the air surroundings consist of many impurities including dirt, but the chimney design didn’t cover and might cause the dirt to fly into the chamber through it and contaminate the food inside.

Another design of solar dehydrator was introduced by Eltawil *et al*., [10]. This design promoted solar-wind ventilation to enhance dehydration performance. To fully utilize the wind energy, a mini-windmill was installed with the chimney (15 cm diameter) to operate the suction fan that was fixed on the vertical steel shaft (1 cm diameter) located in the middle of the chimney. The windmill was assembled by three stainless steel hollow cups of 10 cm diameter which are lightweight and fixed on the top of the steel shaft. However, this windmill design might take up a lot of space as it will produce a rotor diameter of 115 cm when the cups are rotating. In addition, the airflow produced by the suction fan might be unstable due to unsteady wind flow.

The use of small-size dehydrators that are powered by photovoltaic panels and heated by solar thermal energy is still rarely reported. Thus, this paper presents a hybrid photovoltaic-thermal solar dehydrator designed to meet the needs of households and small businesses.

2. Methodology

The design of hybrid solar dehydrator (HSD) process starts with concept evaluation. There are four types of HSD design involved in this stage. Each of the ideas is sketched as shown in Figure 1. Based on Figure 1(a), the height of the legs is relatively higher than the others as the angle of the solar collector box is 55° to the horizontal. There is a solar blower fan at the end of the solar thermal collector box and it is designed with wheels for convenience. In Figure 1(b), the cabinet is relatively smaller than the others and the angle of the solar collector box is 45° to the cabinet. There is a fan at the side of the cabinet in the collector box and it is also designed with wheels. Figure 1(c) illustrated that the angle of the solar collector box is 0° to the cabinet. The tilt angle of the solar collector with a range of 0° to 15° is suitable to receive the maximum solar radiation in any location in Malaysia [11]. There are no wheels, blower or fan in this design. In Figure 1(d), the angle of the solar collector box is 0° to the cabinet. This design is better than concept evaluation 3 because it consists of wheels and a fan on the top of the cabinet.

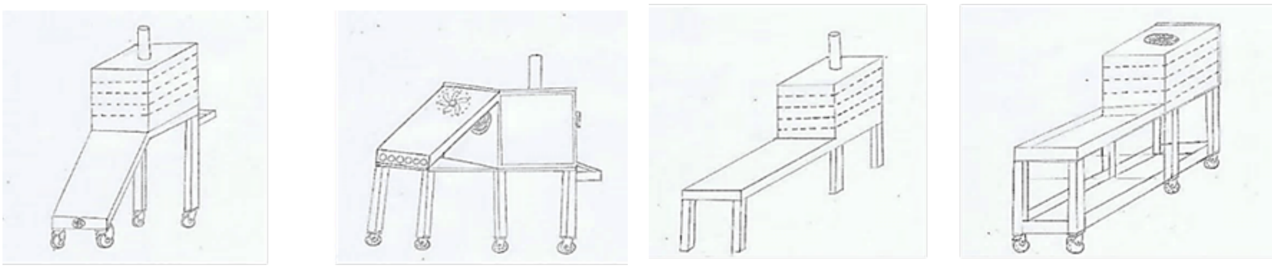


Fig. 1. Dehydrator design concept (a) Concept 1 (b) Concept 2 (c) Concept 3 (d) concept 4

The weighted rating method is used to evaluate the four designs based on the Likert scale weightage criteria with the score 0 to 5 where 0 is the lowest and 5 is the highest. The score for each option is calculated by multiplying the evaluation score and the weighting rate of the criteria. Thus, add all the scores for each option to get the total score. Table 1 shows the score evaluation of each option.

Table 1
Score evaluation of each option

Score	Description
1	Very Poor
2	Poor
3	Moderate
4	Good
5	Very Good

Table 2
Decision matrix table

Criteria	Weighting	Option 1		Option 2		Option 3		Option 4	
		Average Score	Total	Average Score	Total	Average Score	Total	Average Score	Total
Functionality	0.20	3.50	0.70	4.10	0.82	3.00	0.60	4.50	0.90
Size	0.05	4.05	0.20	4.35	0.22	3.75	0.19	3.90	0.20
Quality	0.15	3.65	0.55	3.85	0.58	3.15	0.47	4.25	0.64
Fabrication	0.1	3.60	0.36	3.55	0.36	4.35	0.44	3.85	0.39
Safety	0.20	3.65	0.73	3.85	0.77	3.35	0.67	4.15	0.83
Marketability	0.15	3.50	0.53	3.75	0.56	2.95	0.44	4.00	0.60
Mobility	0.15	4.35	0.65	4.65	0.70	2.90	0.44	4.45	0.67
Total Score		3.72		4.01		3.25		4.23	
Rank		3		2		4		1	
Continue?		no		no		no		yes	

From Table 2, Option 4 received the highest total score while Option 3 received the lowest total score. Thus, Option 4 was selected and approved for the further design process. To clarify the selected concept, the 3D model for the hybrid solar dehydrator prototype is drawn in the CAD software. Figure 2 shows the different views of the hybrid solar dehydrator prototype drawn via SolidWorks 2021.

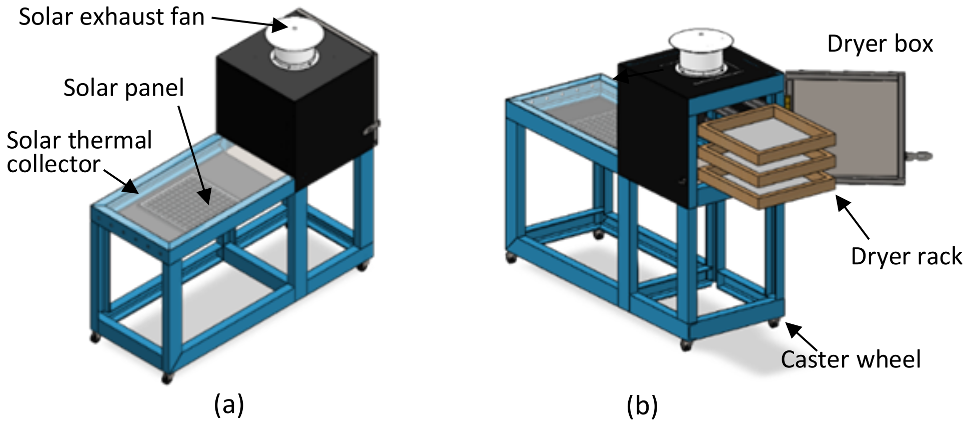


Fig. 2. HSD model (a) Isometric view; (b) Others view

When the prototype is working, the air outside will flow into the solar collector through the inlet holes opened at the front. The air will be heated in the solar collector and flowed into the solar cabinet to help the process of evaporation of fruits and vegetables. The solar exhaust fan at the top will exhaust the air inside the solar cabinet to let new hot air for entering successfully to keep good air circulation in the solar cabinet. The specification of our final prototype and its cost structures is shown in Tables 3 and 4, respectively. Figure 3 shows the picture of the fabricated prototype. The picture on the right is having the door opened.

Table 3.
Specification of the final prototype

Item	Description
Dimension	130 cm (Length) x 50 cm (Width) x 131.65 cm (Height)
Number of Trays	3
Volume of Trays	6.5 Litres per tray

Fig. 3. HSD prototype

The functional test for the hybrid solar dehydrator prototype was conducted in the open field. The traditional drying (TD) method is also conducted to compare the result of drying with the HSD. The vegetables and fruits used in the test are carrot, ginger and banana. All of them are cut into slices of about 2-3 mm. The initial weight of ginger slices is measured as 60 g, while banana slices and carrot slices are 100 g respectively. For dehydrator drying, all fruits and vegetables are placed individually in 3 mesh wire trays and inserted into the solar cabinet. For traditional drying, the fruits and vegetables are put separately in 3 stainless steel trays and placed parallel to each other on the stone bench, which allows them to be exposed to direct sunlight. The test was conducted for 6 hours from 9.00 am to 4.00 pm. The inlet temperature of the dehydrator (IT-HSD), dryer rack temperature (DT-HSD), and exit temperature (ET-HSD) were measured. The ambient temperature (AT) and tray temperature of the traditional drying (TT-TD) were also recorded.

3. Results

Figure 4 shows the temperature recorded on HSD and TD tray during the day from 10 a.m. to 4 p.m. The result shows that the inlet temperature of the dehydrator and the tray temperature for traditional drying increase with time. The hybrid solar dehydrator achieves a peak temperature of 44.1°C at 3.00 pm while the traditional drying achieves a peak temperature of 35.5°C at 2.00 pm. In short, the data have revealed that the solar collector is functioning because the temperature inside the dehydrator is higher than the ambient temperature and tray temperature while figure 6 shows the bar charts of drying rate and moisture loss comparisons.

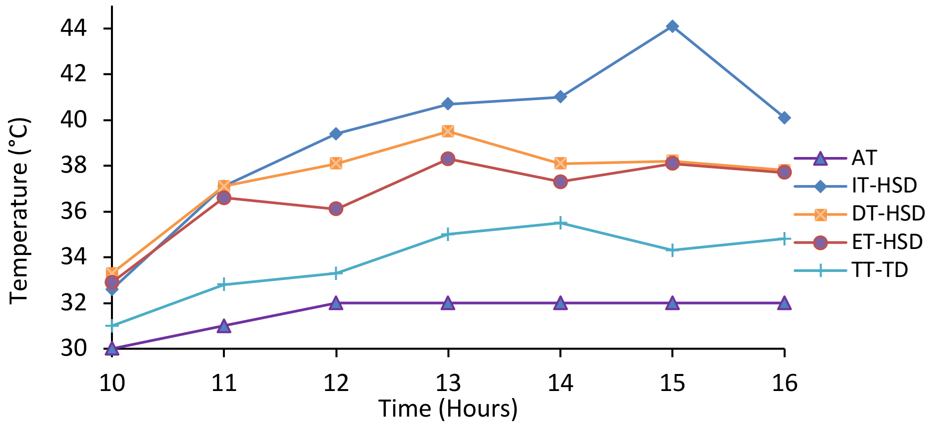
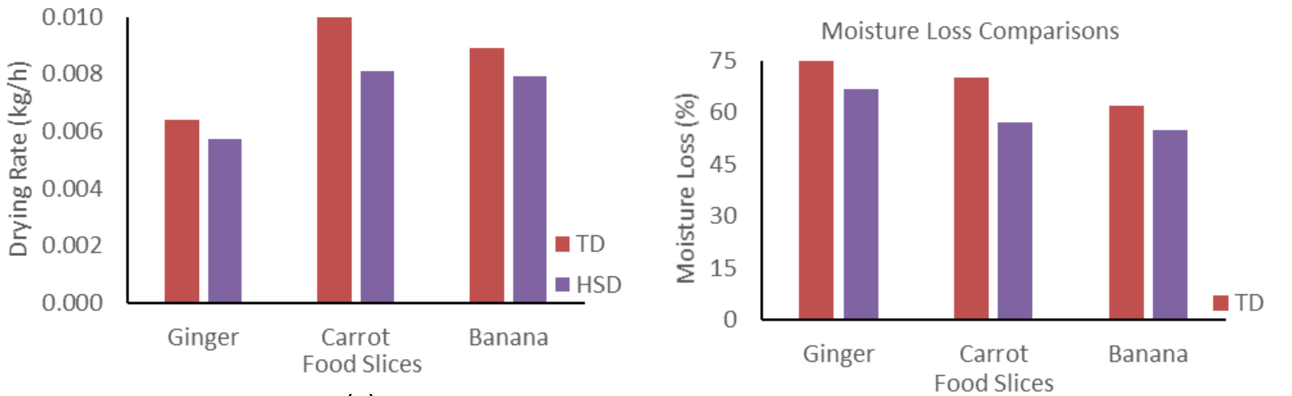


Fig. 4. Temperature recorded at HSD and TD

Based on the bar chart of drying rate and moisture loss comparisons as shown in Figure 5, the drying rate and moisture loss of hybrid solar dehydrator drying are close to traditional drying but both drying methods can cause at least 50% moisture loss to foods in 6 hours. However, the traditional drying method achieves a faster drying rate and higher moisture loss compared with the hybrid solar dehydrator drying. Figure 6 shows the food before and after drying.

From the temperature data, we can observe that the inlet temperature of the dehydrator tends to increase with time. It achieves a peak temperature of 44.1°C at 3.00 pm. Meanwhile, the intermediate temperature inside the drying chamber and exit temperature are lower than the inlet temperature. Both of them are very close to each other. Next, it can be seen that the tray temperature of traditional drying also tends to increase with time. It achieves a peak temperature of 35.5°C at 2.00 pm. In short, the temperature data have revealed that the solar collector is functioning where it raises the temperature inside the dehydrator until it is higher than the ambient temperature and tray temperature. The exit temperature recorded at the exhaust fan outlet is likewise higher than the ambient temperature.

The results showed that the drying rate and moisture loss of hybrid solar dehydrator drying are close to traditional drying. In this functional test, we can observe that both drying methods can cause at least 50% moisture loss to fruits and vegetables in 6 hours. However, the traditional drying method achieves a faster drying rate and higher moisture loss in this functional test. This may be due to the different arrangements of trays. For traditional drying, the trays are put parallel to each other on the stone bench so that the food can be exposed directly to the sunlight. For hybrid solar dehydrator drying, the trays are arranged in layers to utilize the space inside the solar cabinet. Plus, traditional drying is also exposed to the wind, which may boost the drying speed. A 13 km/h of wind speed was recorded on the testing day when it is considered a light breeze.



(a) (b)

Fig. 5. Drying performance comparison (a) drying rate (b) moisture loss

(a) (b)

Fig. 6. Dried food (a) TD (b) HSD

Although this hybrid solar dehydrator provides a slightly slower drying speed than traditional drying, it somehow provides a more hygienic drying environment for fruits and vegetables. Being an enclosed unit, the solar cabinet protects the fruits and vegetables from damage from insects. In this test, we found that carrots and bananas tend to attract flies and ants while drying in the sun (see Figure 7). The presence of flies and ants causes spoilage and pollutes the food during the drying process.

Moreover, traditional drying that exposes the food directly to the sunlight can lead to the photodegradation of food. Ultraviolet (UV) ray is the main cause of this problem as it can break down the chemical bonds of food [12-14]. This process can cause the colour of food products to fade or decrease the quality of products [15]. After 7 hours, it is observed that the texture of fruits and vegetables after TD is darker as compared to drying with HSD (refer to Figure 4). A similar situation was founded in the study of Rehman and Rubab [16] where the sun-dried mint is having a more obvious colour fading effect as compared to solar dried mint. Moreover, a study by Handayani *et al*., [17] also reported that sun drying provides a worse colour result than dried chili. Getahun *et al*., [18] claim that the high relative humidity and prolonged sun drying time substantially contribute to the degradation of carotenoid pigments and the formation of browning compound of chili peppers.

Fig. 7. Insects on carrots and bananas during TD

Apart from that, the fruits and vegetables that exposed under the UV irradiation for TD may lose their nutrition value. Some vitamins are particularly sensitive to UV irradiation in the course of which losses could reach even 50% [19]. Vitamin C, B12, B6, B2 and folic acid are photosensitive water-soluble vitamins, while vitamins A, K and E are photosensitive fat-soluble vitamins. Carotene is a provitamin that sensitive to light. A study conducted by Mohammed *et al*., [20] had shown that open sun drying caused the highest loss of vitamins mostly vitamins A, B6 and C from the dried fruits. This is because the fruits were fully exposed to uncontrolled thermal UV radiations. Ndawula *et al.,* [21] also reported that the open sun drying method caused the greatest b-carotene and vitamin C loss in fruits and vegetables.

Hence, drying via HSD can preserve the colour and nutrition value of food products since there is a layer present between the food products and sunlight source. This may protect the food products from being damaged by uncontrolled UV irradiation. The overall comparisons between the HSD prototype and TD are shown in Table 7.

Table 4
Overall comparisons between traditional drying and hybrid solar dehydrator

Features	Traditional Drying (Sun Drying)	Hybrid Solar Dehydrator
Space Requirement	More space	Less space
Working Principle	Exposed the food directly to sunlight	Dry the food with heat collected from solar radiation
Hygiene	Less hygiene	More hygiene
Nutrition Value Loss	Yes	No
Photodegradation	Yes	No
Exhaust Fan	None (natural convection)	Available (forced convection)

4. Conclusions

HSD is a viable apparatus for food drying. The results of functional test show that both traditional drying and hybrid solar dehydrator can cause at least 50% moisture loss to fruits and vegetables in 6 hours. Although the drying speed of hybrid solar dehydrator is moderately slower than traditional drying, it somehow provides a better hygiene drying environment, and also, preserves the colour and nutrition value of food products. Therefore, since Malaysia receive an abundant amount of solar radiation throughout the year, HSD is a good alternative for cost reduction and is environmentally friendly.

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